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# Applicability of an 'uptake wave' energy transition concept in Indian households

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**Abstract**. Reliable, secure, and affordable energy services are essential to ensuring sustainable economic and social development in the rapidly growing cities of the Global South, yet in India over 30 percent of urban households are still reliant on traditional fuels such as biomass and kerosene for some portion of their energy needs. Understanding the factors that influence energy transitions at a household level, is essential for successful strategies to promote the uptake of cleaner fuels and deliver associated socio-economic benefits. Such fast-growing cities often display intra-urban inequalities of considerable magnitude which can condition individual access to resources and impact the effectiveness of energy provision strategies for individual city districts. In this paper we will use the results of a survey of 500 households in Bangalore, India and explore how this data compares with the 'wave concept' model of energy transition. This 'wave concept' view of energy transitions focuses on appliance ownership as a proxy for energy services and conceptualises the uptake of appliances as a wave with early and late adopters rather than an income-based step change, and as a result better accounts for the role of non-income factors. The wards targeted by the survey cover a range of low-income ward typologies characterised by factors including income, livelihoods, building construction, socio-cultural factors, access to fuels, and reliability of supply. Validating an appropriate model for the uptake of new energy technologies and fuels in households, can better inform policy makers, entrepreneurs, and engineers on the influence of non-income barriers to energy transition across different districts of a city. By understanding how households use energy, and what limits the adoption of more efficient technologies at a local level, city planners and engineers can develop targeted sustainable strategies for adoption of cleaner more efficient fuels and appliances in households.

## 1. Introduction

Reliable, secure, and affordable energy services are essential to ensuring sustainable economic and social development in the rapidly growing cities of the Global South, yet in India over 30 percent of urban households are still reliant on traditional fuels such as biomass and kerosene for some portion of their energy needs. Understanding the factors that influence energy transitions at a household level, is essential for successful strategies to promote the uptake of cleaner fuels and deliver associated socio-

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economic benefits. Fast-growing cities in India (and in the Global South) often display intra-urban inequalities of considerable magnitude which can condition individual access to resources and impact the effectiveness of energy provision strategies for individual city wards and districts. Existing datasets of households do not have sufficient resolution to understand the role that socio-economic and socio-cultural features play in the uptake of clean energy technologies.

Many techno-economic approaches to energy provision and sustainability place an emphasis on monetary terms, and in the process ignore the important role played by socio-economic and cultural characteristics of a household and its immediate surroundings that determine whether a household is more or less likely to adopt a new appliance or type of fuel. In this paper we propose a new model for household energy transitions based on a 'wave concept' accounting for the role of such non-income factors in the differences between early and late adopters of new appliances and fuel at any given income level.

Using the results of a survey of 420 households in 7 city wards in Bangalore, India, we explore the validity of the assumptions underlying such an alternative model for the uptake of clean and modern fuel in an energy transition. Our survey covers a narrow range or 'slice' of the households on low incomes and provides an opportunity to observe the distribution of energy use and appliance ownership at a homogenous income level, while also allowing us to explore non-income variables that are related to these. Identifying a more accurate model for the uptake of clean and modern fuel can help policy makers and businesses better address the needs of individual households and better facilitate uptake of cleaner more sustainable energy use in cities.

## 2. Background

The 'Energy Ladder' concept as a hypothetical representation of the transition of household energy use from traditional fuels such as crop residue, animal waste, or firewood to modern fuels such as electricity and petroleum products assumes that there exists a hierarchy of energy technologies (or fuels) as steps or rungs on the path to clean modern energy use. Accordingly, different fuels on the ladder are ranked by perceived household preference in terms of cleanliness, convenience, and efficiency [1]. This view of energy transitions assumes that households behave like utility-maximising neoclassical consumers, implying that as income rises they will switch to using ever more sophisticated fuels and associated technologies which are higher ranked on the ladder [2].

This concept has certain limitations; Its development was rooted in the need to progress from biomass to so called modern fuels such as electricity and LPG, with the resulting oversimplification that wood fuel is the 'fuel of the poor' [3]. While a range of studies have found income to be an important factor in energy transitions it is not the sole factor influencing the uptake of modern fuels. Indeed an implication of a hierarchy of fuel preferences in the ladder model is that energy transitions are driven "not by an emerging desire for modern fuels so much as by socioeconomic changes, which help to break the constraints on their wider use" [4]. While these constraints can include income, other factors related to the practicalities of access to the fuel can also be an issue.

Early versions of the energy ladder model assumed a clean switch between fuels such that households use one technology at a time as they climb the ladder. In reality many households use multiple fuels to meet their energy needs, especially for cooking. This behaviour is a coping strategy in poorer households where secondary fuels and technologies are kept and used as an insurance policy against unreliable supply or unstable pricing of modern fuels [1]. Indeed many studied based on the energy ladder show some contradiction with the basic assumptions of the model.

Energy provision serves to satisfy a social need and this aspect is often overlooked. Indeed, any techno-economic approach that puts excessive emphasis on monetary terms is likely to result in models that are inaccurate as they do not consider socio-political dynamics and unforeseen innovation [5]. From the perspective of social sciences, recent work considering energy in light of social practices has argued that rather than viewing energy use as a consequence of social systems, energy should be seen as an "ingredient of the social practices... of which societies are composed" [6]

While studies continue to show that, in aggregate, there is a positive correlation between modern fuel use and income [7], it is clear that other factors broaching social, cultural, and political dimensions are still not well understood. There is a lack of suitable and large enough data on these factors [8].

In India, the Indian Human Development Survey (IHDS) is the most comprehensive nationwide dataset on household economic, socio-cultural, and energy use in India [9], however the National Sample Survey Office (NSSO) also carries out regular nationwide surveys on energy use which covers appliance ownership, household fuel use, alongside characterising demographic indicators. The census data offers a snapshot every 10 years. The main limitation of all these national surveys is that despite having nationally representative samples, the sample size at state and district level is often too small to be able to draw conclusions with a relative degree of confidence. This is an issue particularly in urban areas where the existence of intra-city inequalities results in a need for locally tailored strategies, policies, and technologies [10].

## 3. A wave analogy for energy transition

We propose that energy transitions and associated appliance ownership broadly follows ‘waves’ of uptake conceptually illustrated in figure 1. Two distinct groups of appliances were identified from an exploratory analysis of the Indian Human Development Survey (IHDS-II) 2011 dataset:

- Class 1 which are LPG-associated cookware and low-power electrical appliances. Class 1 is associated with an increase in use of LPG by a household and to a lesser degree electricity;
- Class 2 consisting of electricity intensive appliances. Class 2 is associated with a large-scale increase in electricity use.

The rationale behind the wave analogy is that uptake of any technology comprises early and late adopters, and these are not represented in the simple step change model. Geels [11] explains how technology transitions involve the accumulation of niches with specific groups of users shifting to a technology innovation, and this is a gradual process which involves experimentation, learning, and adjustments. Barriers such as information and financing constraints, for example, can slow this process, and the effect of these constraints will vary locally [12].

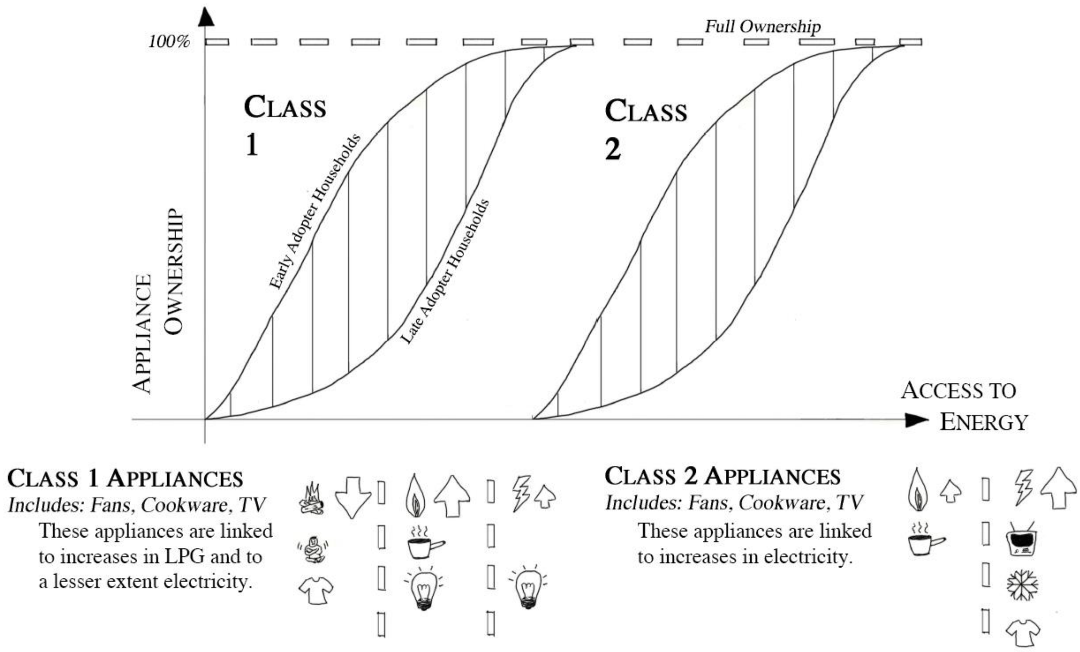


**Figure 1:** Appliance Uptake Wave Concept

Our proposed wave analogy captures the distinction between early and late adopters through the leading and trailing edge of the wave. In figure 1 a graphical representation of these conceptual ‘waves’ are shown with a 'wave' for each class of appliances. The y-axis represents appliance ownership and the x-axis represents either income or access to fuel. Note that each of these waves is bounded by the early and late adopters' curve, and the area between these two is the uptake wave encompassing all other households between these two extreme cases. This conceptualisation satisfies one obvious phenomenon which is that at any given income level households will exhibit a range of appliance ownership levels (and also fuel use mixes); Once the income threshold is satisfied, non-income determinants of household energy use come into play, determining when a household will get swept up in the "accumulation of niches" by a particular technology, and governs whether households are early adopters, latecomers, or somewhere in-between.

This wave analogy makes several assumptions about the distribution of household energy use and appliance ownership, that we set out to verify in this paper. Firstly the wave analogy assumes that at any given income level where appliance ownership of a given class of appliances is present but not ubiquitous, there will be a range of appliance ownership at for households at that income level. The second assumption that follow from this is that what distinguishes early adopters of a appliance or fuel from late adopters are the non-income variables which cover the socio-economic, and cultural dimensions of energy use.

## 4. Survey design

To identify the presence of non-income barriers to energy transitions in Indian households requires an understanding of the multi-dimensionality of factors at the local level where they have the strongest influence. A survey of 420 households across seven wards in the city of Bangalore, was carried out in September 2018 to obtain a suitable dataset. This survey was designed to capture fuel stacking responses to uncertainty, as well as other non-income phenomenon.

### *4.1. Objectives of Survey*

Our survey aims to identify energy use trends and behaviours, directly addressing many of the limitations of these existing datasets. There are three major benefits this survey aims to deliver:

- Resolution - By selecting specific districts and urban and peri-urban wards within cities, and surveying a statistically significant number of households in each, there will be sufficient survey resolution to draw comparisons between these different neighbourhoods of households.

- Detailed Energy Use Breakdown - More detailed questioning on energy use will enable collection of data on the patterns of energy use, the services driving these, and fuel stacking by households.

- Non-income phenomena - By asking a wide range of questions on routines, lifestyle and socio-cultural characteristics alongside the energy use and socio-economic indicator questions, phenomena such as aspirations, time of use profiles, and convenience can be investigated.

### *4.2. Multi-Disciplinary Best Practice*

This survey collects quantitative as well as qualitative data, dealing with subject matters ranging from highly technically-oriented aspects of energy demand profiles, to social and cultural characteristics of households. A wealth of literature in the disciplines of Social Sciences concerns itself with the design of surveys and questions geared towards qualitative data collection. Given the mixed nature of data to be collected for this project, there are valuable lessons to be learnt from survey best practices across disciplines. Central to the design of the survey questions are the following three basic tenets: questions should be understood, questions should be answerable, and answer categories must fit with the intent of the question [13].

*4.2.1. Pre-testing of Questions:* Pre-testing of the survey instrument on a small group of respondents can single out questions that are difficult to understand or are interpreted in a manner other than intended by the researcher. Typically a small group of 15-25 respondents are used for pre-testing with a debriefing session following the survey to understand respondent's experience *[14]*. This survey used a more recent method known as cognitive pretesting where respondents "think aloud" while answering questions to allow interviewers to understand how the question is being interpreted *[15]*.

### *4.3. Design of Survey Instrument*

The design of this survey incorporates the current best practice from social science quantitative survey methods. A series of expert elicitation interviews conducted in Bangalore during April 2018, were an important precursor to the development of this survey, and provides important first hand context, as well as insights on how to ask questions of households.

Table 1 summarises the structuring and types of variables collected by the 142 questions of the survey instrument. An underlying criteria for the design of the survey instrument was to ensure the potential for compatibility and cross-referencing with the existing IHDS and to a lesser extent other NSSO and census data. To allow for this a selection of 34 questions characterising the household in terms of household composition, dwelling type, caste, religion, expenditure, and education were taken from the IHDS-II (2011) survey (across sections 1-4 in table 1).

**Table 1** Summary of survey data types and sections

| Section | Type of Data |
|---|---|
| **1** | Household Identification<br>Socio-cultural indicators e.g. Caste, Migration, Dwelling Type |
| **2** | Household Roster<br>Demographic indicators e.g. Age, No. of People in Household |
| **3** | Occupation and Salary<br>Economic indicators e.g. Occupation, Payment Frequency, Expenditure |
| **4** | Education<br>Socio-economic indicators |
| **5** | Appliance Ownership<br>Ownership of energy related appliances and equipment |
| **6** | Fuel Use<br>Fuel use magnitude, source, and availability |
| **7** | Energy Use Habits<br>Energy use practices e.g. switching behaviours, factors influencing decisions, time of use, access to programmes. |

### *4.4. Survey sample selection*

Correctly selecting the population to sample with this survey is crucial, and the objectives in terms of desired data must be balanced against the logistical and political practicalities of conducting surveys in specific wards or communities within a city.

The results of an expert elicitation survey helped understand the typical energy innovation adopter households both in terms of rural/urban localisation, monthly expenditure, and likely fuel use mix. Coupled with the findings from the IHDS-II this provided a basis for identifying suitable city wards to survey. The limited data available at a city-ward level in the 2011 census including limited data on the type of fuel used for cooking, lighting, and ownership of a group of electronic appliances (TV, mobile phone, radio, scooter) was used to target wards.

From this analysis seven wards were identified, and they are shown and detailed in figure 2 and table 2. These wards are of interest either for being located at a critical point on the appliance uptake wave, prevalence of solar energy systems despite low access to finance or home ownership, or for high use of alternative cooking fuels which imply that households are at a 'tipping point' having to choose between two prevalent options [10].

### *4.5. Sample sizing*

This survey comprises a range of quantitative questions whose purpose is to characterise distribution of energy use and socio-economic variables, as well as qualitative questions with categorisation which will not follow a normal distribution. The selection of sample size for qualitative surveys cannot be obtained purely by calculation and often relies on precedent and best practice [16,17]. However as the quantitative data often requires a greater sample size for statistical significance purposes when compared to similar qualitative survey data, the sample was sized according to key quantitative data.

**Table 2** Selected Bangalore ward characteristics

| Ward No. | Traits of Interest |
|---|---|
| *30* | Relatively high use of solar systems & low access to banking |
| *47* | Low gas use and low access to banking |
| *70* | High proportion of renters, low access to baking and appliance ownership |
| *118* | Low access to banking, and appliance ownership |
| *131* | High use of solar energy, low appliance ownership and gas use |
| *136* | High kerosene use, low asset ownership and access to banking |
| *138* | High kerosene use & proportion of renters, low asset ownership and access to banking |

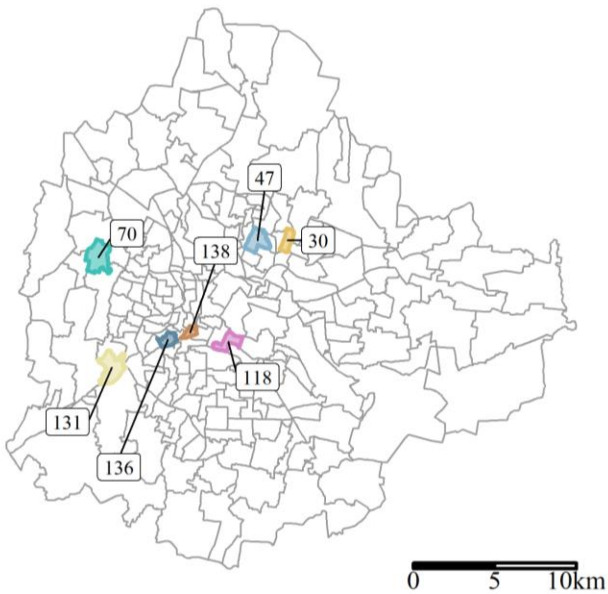


**Figure 2** Bangalore wards selected for survey sample

Recall that one of the objectives of this survey is to have a representative sample of households within each urban district surveyed. As a rule of thumb (Krithikadatta, 2014) a sample size of 30 is sufficient to determine whether the variables associated with households (as summarised in Table 1) follow a normal distribution, provided it is randomly sampled. However, we sized our samples such that we are within a +/- 10% error at a 95% confidence interval for both the continuous and categorical features of the households. A sample size of 60 households per ward was thus selected.

A systematic random sampling method was used which involved randomly selecting starting locations within the ward and knocking on every 10$^{th}$ door down a road to request if they would be willing to participate in the survey, taking a right turn after 10 households. Each of the enumerators would cover between 12 and 15 households. This method is popular in such door-to-door surveys in India due to both its simplicity for enumerators and the even sampling it delivers of households across a ward. While such systematic sampling methods can cause problems in the case of underlying periodicity this was not a likely risk for this survey population. In sum, we covered 7 wards, with a total of 420 households, and 22 key variables per household.

### *4.6. Limitations & considerations*

The descriptive quality and high resolution of our data provide a greater level of detail on energy use habits among low-income slum households in India. However, they are limited in applicability by specifically pertaining to a specific agro-climatic, social, and political geography: namely Bengaluru. Further surveys across different states would be required to test the extent to which one could borrow strength across households located in different physical and socio-political conditions.

## 5. Results & Analysis

One of the stipulations of the wave concept of energy transition detailed above if that at any given income level where a particular class of appliance ownership is not ubiquitous there will be a range ownership levels. The survey sample focused on slum and low-income households which covered a narrow range of incomes with a mean monthly income of 4457 INR with a standard deviation of 940 INR. This provides an opportunity to validate the underlying assumptions of the wave concept. As our sample captured some of the lowest income deciles there was very low ownership of class 2 appliances and thus this paper focuses on class 1 appliance ownership which exhibits a wider distribution of ownership levels.

Figure 3 shows the distribution of class 1 appliance ownership against income. Notice how the range of incomes is well below the mean national income, and follows a narrow normal distribution. While the income range follows a narrow distribution the range of appliance ownership follows a wide distribution between 0 and 60% with a double peak, as anticipated by the wave concept model of energy transition.

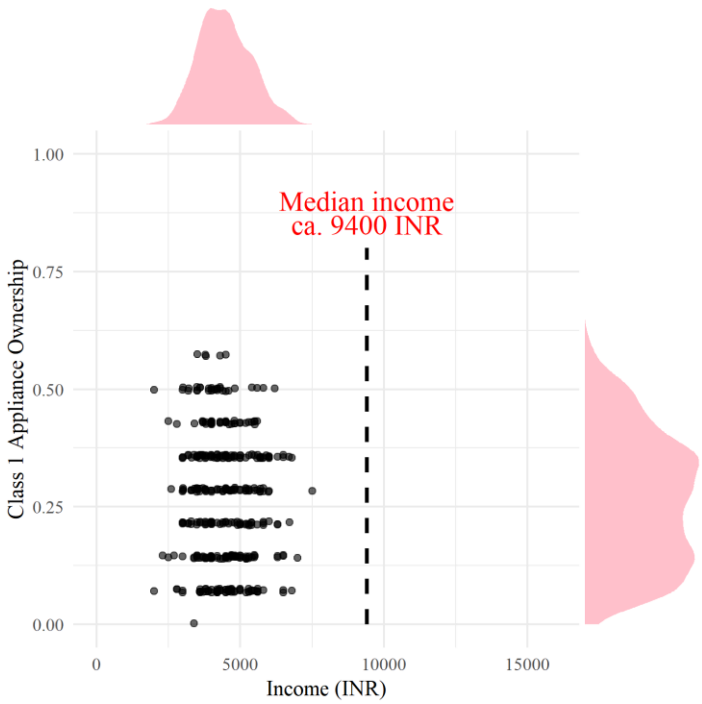


**Figure 3** Class 1 appliance ownership against household monthly income

While our wave concept focuses on appliance ownership as a proxy for energy use, it is of interest to see how this translates in terms of use of modern and clean fuels, such as electricity. Figure 4 shows the distribution of household electricity use and their incomes. Notice similarly how for these households with a narrow distribution of incomes there is a wide range of electricity use. One marked difference is that while most households fall between the 25kWh and 150kWh, 22% of households have

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no electricity use at all. The vast majority of these households do not have an electricity connection which forms a fundamental obstacle to use of this fuel, and rely on batteries and charging kiosks for their electricity needs.

It is of interest to note that the spearman rank correlation coefficient for appliance ownership and income across the households surveyed is -0.05 and similarly for electricity use and household income this is -0.06. Both these coefficients are quite small and indicate that there is no clear monotonic correlation between income and appliance ownership or electricity use. This is an underlying assumption of the wave concept which assumes that within a narrow range of incomes, it is not income that distinguishes household's early or late adopter status, but rather non-income, socio-economic and cultural variables.

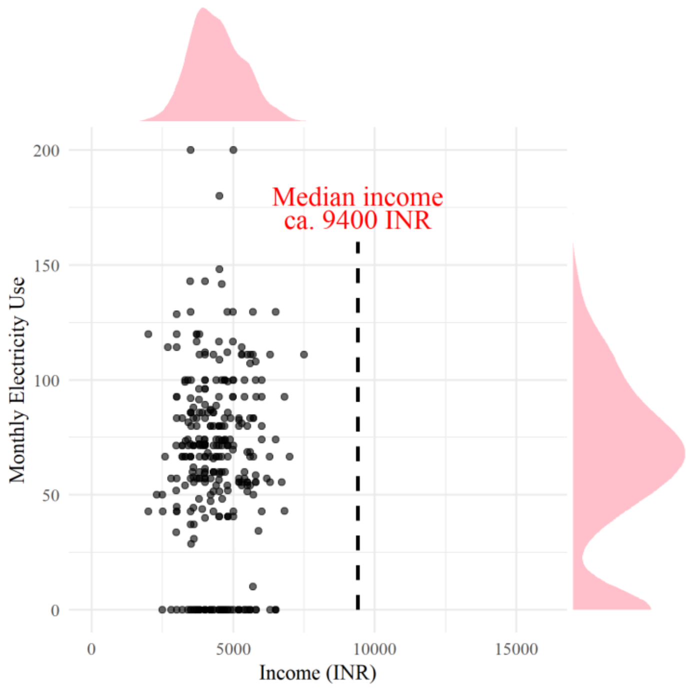


**Figure 4** Monthly electricity use against household monthly income

To test this we conducted a correlation analysis of our 22 key socio-economic and cultural variables with class 1 appliance ownership and electricity use and we and identified several variables which displayed monotonic correlation. Figure 5 shows the spearman rank correlation coefficients with class 1 ownership and household expenditure for a selection of these key indicator variables, notice that several of these are above 0.5 indicating that there is a significant monotonic correlation between these variables and class 1 appliance ownership or household income. Figure 5 clearly shows that while many of the variables that have a significant correlation with class 1 appliance ownership have some correlation with the household's income, with the exception of adequate water supply this is not a significant monotonic correlation, which lends support to the notion that income independent enabling factors are key to appliance uptake and energy transition.

The variables with significant correlation with class 1 appliance ownership cover a range of socio-economic and cultural characteristics of a household and have some intuitive explanations. The correlation with frequency of payment is indicative of the income and job security; households that earn on a daily basis have a constricted cash flow and are often employed as daily wage labourers with little job security and thus will be more reluctant to invest in new appliances, when compared to those who earn weekly of monthly who have greater income security and can afford the risk of investing in a new appliance.

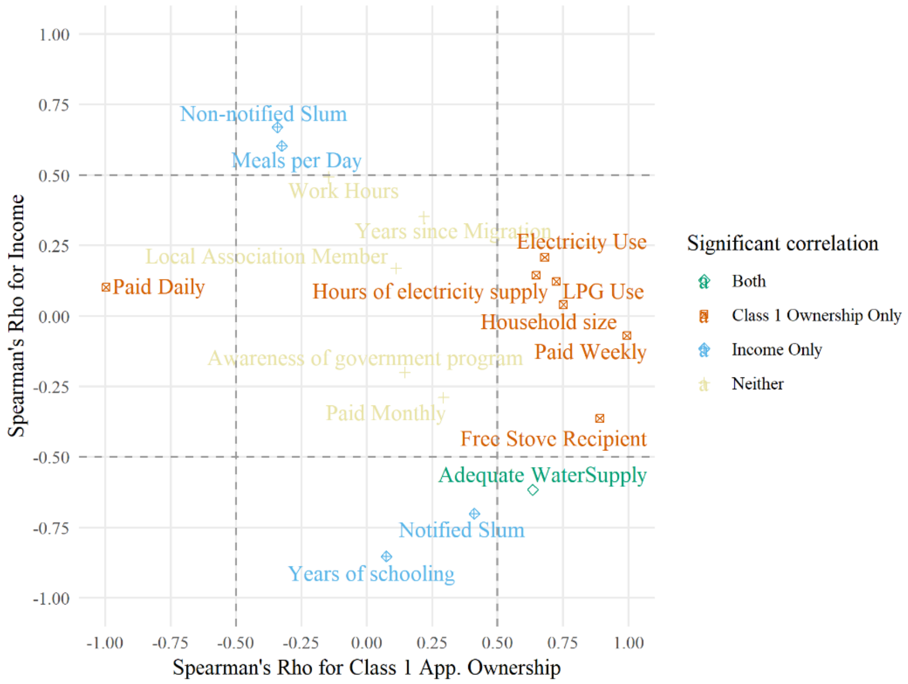


**Figure 5** Spearman rank correlation analysis of non-income household variables against class 1 appliance ownership and household monthly income

Another interesting correlated variable is adequate water supply, which is a measure of how regularly a household has enough potable water to meet its needs. This can also serve as an indicator of access to infrastructure and proximity to utilities, and the strong correlation between these factors suggests that the location of a household within the city and access to other utilities strongly influences their willingness and ability to acquire new appliances and energy services.

In fact when we look at the link with infrastructure access across the 7 wards surveyed, we find some clear cut differences. Wards 47 and 138 have the best water supply and are well established neighborhoods where city utility services are relatively widespread and we find class 1 appliance ownership levels of 30-40%. In contrast ward 70 has the poorest water supply, and is a ward farther from the centre with more recent rural migrants and few streets that have city utilities installed, which is matched with a low appliance ownership of on average 15%.

Several other variables show more minorly significant correlation with class 1 appliance ownership including number of meals per day, and years since migration to the city. The number of meals a day reflects daily routines, and priorities of the household in terms of energy use, while years since migration is an indicator of how settled a household is and the knowledge of surrounding, and family support it could avail of.

The evidence for the wave concept of energy transition this survey provides has some pertinent implications for the way clean and sustainable energy provision is delivered in cities of the Global South. First and foremost the provision of clean and modern energy is not purely a question of household incomes, but is related to a complex mix of socio-cultural and economic variables.

An important implication of the existence of early and late adopter households is that there are households in cities facing different barriers and with distinctly different energy needs. This requires the tailoring of policy and multi-facetted policies and business models to deliver energy services which address these different needs in place of the current tendency to favour one-size-fits-all solutions.

## 6. Conclusions

This results of a survey of a selected 420 low income households in 7 city wards across Bangalore, has shown evidence for the key underlying assumptions of a wave concept model of energy transition in households of the Global South. The results showed that across a narrowly defined range of incomes there is indeed a wide spread of modern fuel use and appliance ownership levels, and that there is no significant correlation with income.

Instead the survey data showed that socio-economic variables related to a household's source of income, access to utilities, household size, years since migration to the city, and number of meals a day were correlated with class 1 appliance ownership suggesting livelihood, geography, and community presence play a role in distinguishing early and late adopter households.

The validation of this wave concept model of energy transition is important as such a model provides policy makers and business leaders with a more nuanced understanding of the different energy needs, and barriers faced by households in rapidly growing cities in the Global South such as Bangalore, and could inform the design of more effective policy and business models for the provision of clean, sustainable, and modern fuel.

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